NBS TECHNICAL NOTE 1248

U.S. DEPARTMENT OF COMMERCE/National Bureau of Standards

Traceability of Laser Interferometric Length Measurements

Howard P. Layer and W. Tyler Estler

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[1]Headquarters and Laboratories at Gaithersburg, MD, unless otherwise noted; mailing address Gaithersburg, MD 20899.
[2]Some divisions within the center are located at Boulder, CO 80303.
[3] Located at Boulder, CO, with some elements at Gaithersburg, MD

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TRACEABILITY OF LASER INTERFEROMETRIC LENGTH MEASUREMENTS

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The National Bureau of Standards maintains the standard of length in accordance with the definition of the meter adopted by the General Conference of Weights and Measures (1983).[1] This standard is used within NBS to form a consistent system of units which are used in NBS calibration services.

LENGTH STANDARD: The meter is defined as "the length of the path travelled by light in a vacuum during the time interval of 1/c = 1/299 792 458 of a second."[2] This definition establishes a fixed value for the speed of light, c, in a vacuum. Neither this definition nor the document which describes it discusses length measurements when the index of refraction is other than unity. Such information must come from other sources.

The realization of the meter for industrial and scientific measurements relies on several types of stabilized lasers operating under specified conditions, for which vacuum wavelengths have been recommended by the International Bureau of Weights and Measures.[3] The wavelengths of these lasers are intrinsic standards. The iodine stabilized Helium-Neon laser operating at 633 nm is the instrument most suitable for the practical realization of the meter because of its high accuracy (about 2.3 parts in 10^{10}), its portability, and the ease with which it can be used to calibrate working lasers.[4] The calibration of a working laser yields its vacuum wavelength and is accomplished by measuring the frequency difference between the working and the standard lasers using a heterodyne photodiode and a frequency counter. This measurement is independent of the index of refraction of air.

LENGTH MEASUREMENTS: For length measurements in air, the wavelength of the calibrated working laser must be adjusted for the difference in the index of refraction, n, between air and vacuum.[5] The wavelength of laser light in air is equal to its vacuum wavelength divided by the index of refraction of air and is smaller by about 2.7 parts in 10^4 for standard atmospheric conditions. For accurate length measurements, the value of the index of refraction must either be measured directly or calculated from an empirically derived formula based on such measurements.[6] The variables which most strongly affect the value of n are temperature, relative humidity, barometric pressure, and CO_2 abundance. The accuracy of the calculation using the empirical formula is limited to about 1 part in 10^7 when state-of-the-art technology is used for measuring these four parameters.

LASER INTERFEROMETER SYSTEMS: Relating practical laser interferometric translation measurements to the length standard is difficult because the meter is defined in terms of a vacuum wavelength whereas length and translation

measurements in the laboratory and shop are made in air. To account for this difference, laser interferometer systems incorporate transducers for measuring atmospheric conditions and the algorithm for computing the wavelength in air, all of which must be correct in order for measurements to be accurate to within stated uncertainties.[7] Consequently, meaningful traceability of displacement measurements using laser interferometer systems to the NBS must be concerned with the total accuracy of the length measurement and not with laser calibration alone.

TRACEABILITY: The National Bureau of Standards supports laser interferometer system manufacturers to ensure the traceability of length measurements by providing technical information and assistance. In particular, NBS has developed a portable Iodine Stabilized HeNe Laser (633 nm) to ensure that manufacturers have access to the length standard at an accuracy of 2.3 parts in 10^{10}. In addition, NBS provides technical support and information to interferometer users when they encounter unusual problems which cannot be solved by using commercial equipment or services.

Calibration of individual laser interferometer systems at NBS is insufficient to ensure that subsequent measurements made using that system in other environments will be correct. Unlike gage blocks and other simple artifacts, the operating characteristics of laser interferometer systems are known to change after calibration, especially when the systems are transported and are turned on and off frequently. The long term accuracy of laser interferometer systems is determined by the manufacturer based on experience gained by comparing their system with one of higher accuracy over extended periods of time. The laser wavelength accuracy and stability can be measured by comparison with an iodine stabilized laser and the index of refraction correction accuracy by comparison to laboratory grade temperature, pressure, relative humidity, and CO_2 measuring instruments. This information should be incorporated into the specifications provided with the instrument.

In consideration of the above information, NBS believes that the traceability of stabilized lasers and laser interferometer systems to the National Bureau of Standards must proceed from the user through the manufacturer to NBS. We know that the calibration of individual lasers or laser systems does not characterize their long term accuracy and, thus, this service is not provided by NBS.

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1. NBS Special Publication 330 (1986).

2. Comptes Rendus des Scéances de la 17e CGPM, 1983.

3. Metrologia 19, 163-177 (1984).

4. H.P. Layer, IEEE Trans. Instrum. and Meas., IM-39, 358 (1980).

5. F.E. Jones, J. Res. Nat. Bur. Stand. (U.S), 86, 27-32 (1981).

6. W.T. Estler, Appl. Opt., 24, 808-815 (1985).

7. Hewlett-Packard Jol., 34, No. 4 (Apr. 1983).

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